IBM research

PROJECT LIGHTNING

tenth quarterly progress report

and final summary

Volume I

PROJECT LIGHTNING
Tenth Quarterly Progress Report
(1 March 1961 to 31 May 1961)
and Final Summary
(Contract NObsr 77508, Task 4)

Volume I

International Business Machines Corporation
Research Center
Yorktown Heights, New York, 31 July 1961

Contents

Contents (Continued)

I. INTRODUCTION

This is the final report on work supported under Contract NObsr 77508, Task 4, and the tenth of a series of quarterly progress reports which began with the initiation of Task 3 under this contract.

The IBM Lightning program was a study aimed toward the design of a computer system capable of performing basic logic operations at a rate of 1000 megacycles.

The program was composed of three separate phases.

Phase I, which was Task 15 of Contract NObsr 63472, covered the period from 6 June 1958 to 31 December 1958, when three promising technologies were studied. These were: microwaves and intermediate-frequency logic, solid state physics and logic, and cryogenics. A smaller machine-organization effort was also included. A series of five numbered progress reports and a final report (Final Progress Report, Task 15, Vol. I and II) were written concerning the work done during this period.

Phase II extended from 1 December 1958 to 31 May 1960. During this period 85 percent of the work was devoted to cryogenics and the associated machine organization. The remaining 15 percent of the effort was directed toward high-speed semiconductor devices and symbolic logic. During this period six quarterly reports were written. The final report was contained in the sixth report.

Phase III covered the period from 1 June 1960 to 31 May 1961. The entire program has been devoted to cryogenics and associated machine organization efforts. Quarterly progress reports numbered six through nine described the work, and this is the tenth, which also contains the final report for the period.

This report is issued in two volumes. The first contains the progress made during the final quarter and two summaries. The first summary covers the work done during the contract period and contains a review of the state of the art and recommendations for the technology and device areas. The second summary covers similar aspects of the machine organization effort. The second volume contains a series of appendixes which are detailed technical reports of certain phases of the work that have been completed.

2. CRYOGENICS

2.1 GENERAL

As with previous reports on the work in cryogenics, this report covers only the Lightning-supported portion of the total IBM effort in cryogenics. This work includes four major areas: physical characterization of components (2. 2), associated circuit problems (2. 3), device and circuit fabrication techniques (2. 4), and physical chemistry of thin films (2. 5). Additional programs in the theory of superconductivity and low-temperature materials and technology, including work on thin films and some on circuitry, are not receiving Lightning support and therefore are not reported here.

2.2 PHYSICAL CHARACTERIZATION OF COMPONENTS (N. H. MEYERS)

The major objectives of this effort are to establish and understand the static and dynamic electrical and thermal characteristics of various types of thin-film superconductive switching components and to relate these characteristics to circuit operation.

2.2.1 Studies of Static Electrical Characteristics of Cryotrons

2.2.1.1 General Objectives

As pointed out in earlier reports, the most promising type of thin-film cryotron for high-speed circuit operation is the multiple-control in-line cryotron. This effort is intended to establish those static electrical properties of such cryotrons which are important in circuit operation. In particular, it is necessary to know:

1. incremental current gain as a function of thickness and temperature,
2. sharpness of resistance transition induced by control current, and
3. the extent of field and thermal hysteresis.

These properties must be compared for various gate materials and conditions of fabrication. Attention must also be paid to the reproducibility of results.

2.2.1.2 Status

All cryotronic components and circuits to be discussed in the present report were fabricated in conventional evaporators without the aid of prenucleation, substrate heating, or ultra-high vacuum.* In Appendix I of the present report, A. Brennemann gives some general results on the properties of gate films of both tin and indium made in conventional evaporators and compares these results with those from films made under more refined conditions by A. Toxen and H. Caswell. In addition, Brennemann gives some limited data on the reproducibility of gain characteristics of simultaneously evaporated in-line cryotrons of indium at a common operating temperature. Finally, the gain characteristics of crossed-film cryotrons of both tin and indium are discussed.

* Cryotrons have been made by some of these techniques at Kingston in FSD, but the results are not discussed in the present report.

The principal conclusions of Appendix I are as follows:

1. The magnetic transition and hysteresis characteristics of indium films made in the conventional device evaporators are very close to those of films fabricated under ultra-high vacuum conditions. Films made under conditions of normal vacuum with mechanically trimmed edges and cooled substrates apparently have slightly sharper magnetic transitions and narrower hysteresis loops.

2. Four indium in-line cryotrons evaporated at the same time on the same substrate were compared at the same typical operating temperature. Percentage transition widths for control current switching were larger than for external magnetic field switching. Evidently control current does not produce a uniform field over the entire gate width.* Critical field values across the substrate were more nearly reproducible than critical control current values. This is a consequence of either shadowing, misregistration, or inability to maintain constant control line width. It should be possible to correct these difficulties by using more refined techniques in the fabrication of the control lines.

---

* This may be partly due to shadowing or misregistration at the edges of the control. However, copper model studies show an appreciable decrease in field strength near the gate edge even with perfect geometry. The two-dimensional nature of the field problem is responsible for appreciable field penetration of the control edges even when the control film is several penetration depths thick.

3. The combination of magnetic hysteresis, variation of critical control current from one cryotron to the next, and width of control current-induced resistance transition sets a minimum value on the control current signal which can be used in a circuit energized by common bias and working current supplies if full resistance operation is to be achieved. A maximum value on the control current signal which can be used is set by the value of gate current at which the incremental gain of the poorest cryotron falls below unity.

In-line cryotrons from conventional evaporators with tin gates have such broad magnetic transitions that the maximum permissible control signal is much less than the minimum value needed for full-resistance operation. With indium gates the situation is more favorable. In this case the maximum permissible control signal is about equal to the minimum value needed for full-resistance operation. However, this leaves no margin of safety in setting the bias and no overdrive for high-speed switching of the gate. Consequently, the static properties of in-line cryotrons made in the conventional device evaporators thus far are not satisfactory for use in circuits fed from common supply and bias current sources. As a result of these and other findings, extensive upgrading of the device evaporators is being undertaken.

4. Critical temperatures of indium films are more reproducible than those of tin films evaporated under similar conditions.

5. Experimental values of dc critical current for both tin and indium films above a Pb shield plane are quite irreproducible and tend to be 50 to 80 percent of the values predicted by the critical current density switching hypothesis. It is obviously desirable to increase the critical current values to as great an extent as possible. Fortunately, for biased operation, the critical current need not be as reproducible as the control current, although the circuit operation will be limited by the lowest critical current displayed by a collection of devices.

6. The static gain characteristics of crossed-film cryotrons are also rather irreproducible. The characteristics of the cryotrons having equal gate and control widths show incremental gain greater than unity only over a very limited range of gate currents. The static gain is qualitatively predicted by a macroscopic theory which uses a critical current density switching hypothesis for self-current and a free-energy hypothesis for control current switching. The measured static gain is 30 to 40 percent lower than that predicted by the simple theory. This is in agreement with the low values of critical current discussed under conclusion 5 above.

2.2.1.3 Recommendations for Further Investigation

1. Devices with indium gates should be stored at reduced temperature to find out whether the diffusion of Pb connections, mentioned in the ninth quarterly progress report, can be stopped in this simple manner. Work should also be done to see whether diffusion barriers can be used to eliminate the deterioration which otherwise takes place at room temperature.

2. The characteristics of indium-based, tin alloy cryotrons should be measured. Potentially these offer the advantages of higher resistivity than tin plus the better reproducibility and sharper transitions of indium.

3. Means of achieving narrower magnetic hysteresis loops (as, for example, prenucleating to achieve fine-grain films) must be used to produce usable devices. At present it appears that narrower hysteresis loops plus sharper control current-induced resistance transitions are needed to permit full-speed operation of circuits fed by common bias and supply current sources.

2.2.2 Studies of Dynamic Electrical Characteristics of Cryotrons

2.2.2.1 General Objectives

The properties of any electronic component or system are frequency-dependent. In the case of thin-film cryotrons, certain properties can be expected to deviate in a nonnegligible way from their static behavior. In addition, certain effects not present at low frequencies can be expected to appear and have a significant influence on component and circuit operation at high speeds. The objectives of this program are to develop suitable instrumentation and devise experiments to investigate dynamic properties of thin films and thin-film cryotrons such as:

1. the switching speed of indium and other films, subjected to a pulse of a tangential surface-field, as a function of film thickness, temperature, resistivity, and amplitude of driving field;
2. the switching speed of components imbedded in cryotronic circuits;
3. pulse gain and dynamic resistance transition characteristics of cryotrons;

4. pulse reflection and transmission properties of various cryotron geometries imbedded in transmission lines;
5. inductive and capacitive coupling effects among control, bias, and gate lines; and
6. the relationships between component characteristics and circuit behavior.

Naturally, these effects are interrelated. Furthermore, the program outlined above is a large one. Consequently, work must proceed as a series of carefully chosen experiments in which efforts are made to isolate and observe pertinent effects.

2.2.2.2 Status

Construction and debugging of the high-sensitivity sampling apparatus mentioned in the eighth and ninth quarterly reports is complete. The electronics performs satisfactorily. However, a coupling problem between drive line and sense line is so bad that the desired signal, representing the switching speed of a film, is swamped out. Better shielding may ease but will probably not eliminate the problem. Basically, the trouble stems from use of high-impedance (50-ohm) drive and sense lines in an experiment on a low-impedance

(of the order of 1/2 ohm) device. Possibilities of fabricating low-impedance strip lines are being investigated.

As pointed out in the ninth quarterly report, measurements of the switching speeds of thin films are not directly indicative of attainable circuit speeds. Hence plans are being made to measure the delay per stage in a thin-film circuit in which one externally driven flip-flop in turn drives a second flip-flop. The circuit has been redesigned to permit easier short detection and the masks are being punched.

It is well known that pulse critical currents of evaporated gate films are quite different from the dc critical currents of the same gates. Furthermore, limited experimental work reported in the eighth quarterly progress report suggests that pulse critical fields may differ from their dc counterparts. Therefore, it seems important to establish the gain characteristics of various cryotron structures under conditions of pulse operation. A device for such an experiment has been designed, the masks have been punched, and fabrication of devices is scheduled to begin following additional modifications of the device evaporators.

2.2.2.3 Recommendations for Futher Investigation

One serious instrumentation problem involved in all of the experiments just mentioned in Section 2.2.2.2 is that of coupling between drive and sense lines. It now appears that the most satisfactory way to overcome this difficulty is through use of drive and sense lines which are matched to the impedance of the thin-film structure under test. Furthermore, the power which must be supplied by an external generator, feeding signals to a thin-film circuit, is proportional to the impedance of the line connecting generator and circuit.

The most promising approach toward low-impedance lines is a strip-line structure using thin mylar or teflon tape as the dielectric. Nickel and copper can be deposited on mylar by an electroless process. Copper-clad teflon is commercially available. Work should be done to establish the electrical propagation properties of such lines. Since thermal conduction will also be important in such lines, their electrical characteristics must be studied in conjunction with their thermal conductance. In an engineering sense, the work done on plated magnetic tapes should be of considerable value here.

2.2.3 Static and Dynamic Thermal Properties of Cryotrons

2.2.3.1 General Objectives

The over-all objective is to determine the nature and scope of problems associated with joule heating in thin-film cryotronic circuit operation. The approach is to measure the thermal properties of an individual cryotron and to synthesize a mathematical model characterizing these results. Knowing the thermal behavior of one component and the thermal coupling between components on the same substrate, one can analytically establish the thermal limitations upon speed of simple circuits. Extension of such analysis to more complex systems also seems feasible.

At present, the experimental work is aimed at measuring:

1. The total thermal conductance of a gate on a substrate when immersed in a liquid helium bath. The total thermal conductance K in watts / ^{o}K is defined as

$$K = \frac{P_{av}}{T_{av}}, \qquad (1)$$

where T_{av} is the time average rise in gate temperature (above the bath temperature) when time average power P_{av} is supplied to the gate. K is to be determined as a function of power, temperature

rise, cryotron dimensions, and substrate material.

2. The thermal coupling between gates as a function of the same variables stated in the preceding paragraph.

2.2.3.2 Status

The following work is discussed in detail in Appendix II of the present report.

Dr. H. Sobol has found that the surface transfer coefficient h from a glass substrate into a helium bath is a strong function of temperature rise above the bath temperature. Both the total thermal conductance K from a tin gate on a glass substrate to the helium bath, and the temperature distribution T(x) over the substrate are strongly dependent on h. The experimental variation of K with gate length, gate width, and power level requires a highly nonlinear h for reconciliation with analysis. The same nonlinear h also permits reasonable agreement between measured and predicted T(x). The nonlinear behavior of h also partly explains the earlier reported discrepancies between h deduced from cryotron measurements and h as measured directly in experiments using simpler geometries. At present, the static thermal properties of cryotrons on glass substrates seem fairly well understood. A few dynamic cooling

curves for cryotrons will be measured in an effort to show that the variations of h with temperature rise above bath also explain the variations in the apparent time constant of the cooling.

Dr. Sobol has attempted to extrapolate the present understanding of K for a single cryotron to a system of continuously operated, thermally coupled cryotrons. He has found that the thermal problem is eased as the conductivity k of the substrate is increased, but that a point is reached where the substrate is essentially isothermal and no appreciable improvement can be realized by a further increase of substrate conductivity. Approximate analysis indicates that the point of diminishing returns in a typical case may be of the order of $k = 150$ mw/cm^{o}K. This is to be compared with $k = 1$ for glass. However, the value of k required for an essentially isothermal plane of circuitry depends on many factors, such as the temperature rise to be tolerated, the cryotron dimensions, the packing density of components, the substrate thickness, and others.

Other conclusions of Appendix II are:

1. The total conductance of a gate is roughly proportional to gate area for fixed power dissipation per unit area.

2. Miniaturization of cryotron dimensions contributes greatly to the realization of high packing densities within the limits of the thermal problem.

3. Electrical design to permit circuit operation in spite of large substrate temperature rise above bath should also increase the packing density because the nonlinear nature of h is then most effectively exploited.

4. Substrate materials having thermal conductivities of the order of 1 watt/$^{\circ}$K-cm, or greater, at liquid helium temperatures are required for very densely packed computers.

2.2.3.3 Recommendations for Further Investigation

1. The static thermal properties of cryotrons on substrates of high thermal conductivity should be measured. Promising materials are aluminum and copper. Niobium is not as promising as either of these two materials from a purely thermal standpoint but has the added advantage of being a hard superconductor. Thus, it might be more appropriate as a combination ground plane and thermal conductor.

2. Because of the irreproducible nature of gate self-current measurements, future thermal work should attempt to exploit the critical field of the gate material as an indication of gate temperature.

3. Means of miniaturizing cryotron dimensions without generating impossible registration prnblems should be investigated.

2.3 ASSOCIATED CIRCUIT PROBLEMS

2.3.1 Subtractor-Ring Circuit

2.3.1.1 Objectives

A subtractor-ring circuit was discussed in the seventh quarterly Lightning report. The circuit was designed with two purposes in mind. First, it should provide a check on the validity of a computer program written to simulate the operation of cryotronic circuits. Secondly, it should provide a convincing demonstration of the ability of cryotronic circuits to perform the type of logical operations called for in a computer.

2.3.1.2 Status

Partial operation of several subtractor-ring circuits was described in the ninth quarterly Lightning report. It has been found that the clocked-ring portion of the circuit is too fast in its operation for the subtractor portion to keep pace. The circuit has been redesigned by J. McNichol and the unusable clocked-ring portion eliminated.

One problem which arose in testing the subtractor-ring circuits was the rapid exhaustion of the liquid helium supply. Only an hour or so of testing time was available before new helium was needed. This was a consequence of the use of many input cables and of a small 1-1/2-liter dewar. A much larger (5-liter) dewar is currently being made operational. Furthermore, the input cables and sample holder have been designed to minimize the conduction heat leak, and nitrogen precooling of the leads has been provided. The sample holder should be completed shortly. It is anticipated that at least eight hours of testing time will be available before exhaustion of the liquid helium supply.

Every device developed shorts during the testing operation, usually immediately after immersion in liquid helium. These were cleared by passing a sufficiently large current through the short without apparent damage to the device, and testing proceeded. The occurrence of this type of short should be less frequent with the new dewar arrangement because the time between temperature cycles will be increased. This problem is considered a serious one with complex circuits, however, and we hope that modifications currently being made in the device evaporators will reduce the number of shorts.

2.3.1.3 Recommendations for Further Investigation

Work on circuits of this type should be resumed when the device evaporators are operating satisfactorily.

2.3.2 Coupling of Circuits on Different Substrates

2.3.2.1 Objectives

The objectives are stated in the seventh and eighth quarterly Lightning reports.

2.3.2.2 Status

Work in this area has not progressed this quarter because fabrication facilities have been dismantled for modification and transportation to a new location.

2.3.2.3 Recommendations for Further Investigation

1. An evaporated transformer should be used to couple

two halves of a flip-flop to determine speed capabilities of this type of coupling.

2. A low-impedance transmission line should again be used to couple two halves of a flip-flop. Improved shielding at the lands should be used to provide lower inductance and better speed.

2.3.3 Trapping of Stray Magnetic Fields in Ground Planes

2.3.3.1 Objective

The general objective of present work on trapping of stray fields is to find suitable means of eliminating them.

2.3.3.2 Status

A. E. Brennemann has found that flux associated with the earth's magnetic field can be trapped in the ground plane of a device when the sample is immersed in helium and the lead (Pb) ground plane switches from normal to super. In other words, the ground plane frequently fails to completely expel the earth's field as it passes into the intermediate state from the normal state. The field

strength associated with the trapped flux depends on the orientation of the sample relative to the earth's field as the sample is immersed. The trapped flux can provide sufficient field strength to reduce the critical current of a tin gate above the ground plane by as much as a factor of two. The experimental results are reported in detail in Appendix III of the present report.

Brennemann has shown that the reduction of gate critical current due to the trapping of some of the earth's flux can be eliminated by providing a field-free region just above the surface of the liquid. He has also replaced the earth's field by a much stronger field generated by a pair of Helmholtz coils. The effect described was amplified.

Flux trapping also occurs in the ground plane during circuit operation. Films made of materials having very high critical fields offer the possibility of preventing this type of flux trapping.

Dr. Kahan has been successful in preparing superconducting films of niobium nitride by reducing $NbCl_5$ in hydrogen, vacuum firing the resulting film to convert it from a hydride to niobium, and then heating the niobium in a nitrogen atmosphere to produce the nitride. A film made in this manner had a critical temperature of about $14^{\circ}K$ and a temperature transition width of 1°.

2.3.3.3 Recommendations for Further Investigation

Further work on the problem of flux trapped when the device is immersed in helium is not warranted since it is easily eliminated by providing a field-free region.

The next step in the niobium nitride film work will be to improve the techniques so that a film of uniform thickness can be made and to try this film as a ground plane for a device in which flux trapping can be measured.

2.4 CRYOGENIC DEVICE FABRICATION (I. AMES)

2.4.1 General Objectives

The main objective of this project is to produce usable cryogenic thin-film circuits. Emphasis is directed primarily at 1) putting into practice as quickly as possible the improvements in the fabrication of superconducting and insulating films developed by other groups within the Cryogenics Department, and 2) identifying and solving problems peculiar to and fundamental to fabrication of multiple-layer thin-film cryogenic devices.

2.4.2 Status

The program during this past quarter has been directed mainly toward an upgrading of the present device fabrication facilities. Improvements in vacuum conductance to the vicinity of the masks and substrates are being carried out. Uncontrollable sources of gas within regions subjected to heating during the evaporation process are being eliminated wherever possible. For example, the use of baked-on silver paste lands (applied prior to film deposition) has been discontinued. Epoxy resins present in the vicinity of the masks, substrates,

and shutters have been replaced by all metal components. The power input system for the evaporant sources has been increased in capacity, and line losses in series with the evaporant source have been reduced from 50 to about 25 percent. This has made it possible to raise the sources to temperatures high enough to efficiently outgas them prior to use with evaporants. Pumping methods have been modified to minimize back-streaming of pump vapors into the evaporation chamber. The cold traps within the system are removed and cleaned after each cycle of operation.

2.4.3 Recommendations for Further Work

A cryogenic pump, designed jointly with H. Caswell, will be inserted in the 18-inch device evaporators. Previous experience has indicated that this type of pump should make it possible to achieve system pressures low enough to facilitate edge-breakaway of the superconducting films, a necessary prerequisite to sharp transitions. Ionization type evaporation-rate monitors will be installed directly above the substrate region to provide accurate control of film thicknesses. Further work will be undertaken on 1) molybdenum oxide insulating layers, with the hope that device

insulation will be improved, and 2) anodized niobium substrates, in order to minimize flux trapping in ground planes.

2.5 PHYSICAL CHEMISTRY OF THIN FILMS (P. WHITE)

2.5.1 Surface Photolysis

2.5.1.1 General Objective

A new technique of producing thin-film circuits is being investigated. In certain cases, adsorbed gases may be selectively decomposed by ultraviolet light photolysis. When a surface containing adsorbed gases is illuminated in a definite pattern, photolysis occurs only on those sections of the surface exposed to the light. Three separate possible reactions are being considered - those in which:

1. the adsorbed gas is an unsaturated hydrocarbon, like ethylene, allowing the free radicals formed by photolysis in the adsorbed layer to form a polymer film,

2. the adsorbed gas is one which on photolysis forms free radicals capable of reacting with the metal film to form a volatile metal compound, thus removing metal from the film, and

3. the adsorbed gas is one which decomposes on photolysis to form metal and a volatile compound.

This is, then, a possible method of preparing thin-film metal circuits or fabricating thin insulating films, merely by admitting a suitable gas and projecting the required pattern with ultraviolet light. Since it is only necessary to project the pattern onto the substrate, it is possible to reduce the size of the circuit optically, thus allowing the possibility of microminiaturization without the need for fabricating extremely fine masks. In theory, the resolution of the method should be limited only by the resolution of the light beam.

The main objects of this project are to prepare insulating films by surface photolysis which can be compared with insulating films currently being prepared by evaporation, and to fabricate a thin-film circuit by etching a tin film in order to evaluate the definition achievable by this method.

2.5.1.2 Status

The investigation of the surface photolysis technique of preparing insulating films has continued. Various metals have been used as underlayer and have all been successfully insulated with

polymer films about 300 Å thick. Insulating films have also been made by using an electron beam to decompose adsorbed gases. The films formed in this way have electrical characteristics similar to those formed by photolysis of adsorbed gases. It is known from experience that greater difficulty with shorts is encountered when fabricating multilayer structures. Consequently, equipment has been designed and built to enable multilayer polymer insulating films to be made in a conventional bell jar evaporator. This will permit a more realistic evaluation of the use of polymer films in cryotron components.

Preliminary experiments, designed to determine the mechanism of surface photolysis reactions, indicate that a minimum light intensity is required before polymerization takes place. Below this minimum intensity only an enhanced sorption of butadiene is observed after shining light onto the surface.

2.5.1.3 Recommendations for Further Investigation

Potentially, the surface photolysis experiments are important, since, in addition to polymer formation, the technique can be utilized to both deposit metal in predetermined circuit patterns and to etch circuit patterns from an evaporated metal

film, by suitable selection of adsorbed gas. Further, this is a possible method for preparing microminiaturized circuitry since the size of the circuit pattern can be reduced optically and present problems concerning mask fabrication can be circumvented.

It may be anticipated, from examination of sticking coefficient data, that continuous polymer films will be produced at thicknesses very much less than those required to form continuous insulating films by evaporation techniques. The polymer film should have a strong adhesion to the metal surface since, prior to polymerization, a chemisorbed bond will probably be formed between the original gas molecule and the metal surface, and it is not expected that this bond will be changed by polymerization. This technique has the further advantage that circuits could be fabricated on large area substrates without the difficulties currently anticipated with evaporation techniques.

It is strongly recommended that the work described above be continued.

2.5.2 Nucleation of Molecular Beams on Metal Surfaces

2.5.2.1 General Objectives

The efficiency with which short-free silicon monoxide evaporated layers can be prepared appears to depend on both the nature and surface structure of the underlying metal film. This may be attributed among other things to formation of a metal oxide under the silicon monoxide layer and to a nucleation phenomenon of the silicon monoxide molecular beam on the metal surface.

Initial attempts to study the nucleation problem utilized a simple apparatus similar to an electron scanning microscope, described in Appendix V. The sensitivity was not sufficiently great, however, to yield the desired results. Currently, nucleation of silicon monoxide on metal surfaces is being studied by measuring sticking coefficients of the silicon monoxide molecular beam as a function of surface coverage. This is done by observing the rate of growth of the silicon monoxide film on a metal surface exposed to a silicon monoxide molecular beam of constant density. The information obtained will indicate the thickness of silicon monoxide required to completely cover metal surfaces of various types. In

addition, data will be obtained on the adhesion energy of silicon monoxide to the underlying metal.

2.5.2.2 Status

Preliminary measurements have been made of the sticking coefficient of silicon monoxide on an evaporated tin film. If the tin film is not exposed to pressures greater than 10^{-7} mm prior to deposition of silicon monoxide, the sticking coefficient does not vary with film thickness. When the tin film is exposed to 10^{-4} mm pressure of air for a few seconds prior to the experiment, the sticking coefficient is initially low, about 0.3, then rises to 1 when the silicon monoxide layer is about 150 Å thick. Apparatus has been designed and is now being built to measure condensation energies of silicon monoxide on metal surfaces by observing the temperature above which no condensation takes place for a known molecular beam density. This will yield an estimate of the adhesion energy.

2.5.2.3 Recommendations for Further Investigation

The preliminary results described above indicate the importance of nucleation studies in determining the optimum conditions required for formation of short-free insulating films.

The adhesion of the insulating film to the underlying material is important since it relates to the serious problem of peeling which is encountered when evaporated silicon monoxide films on metal are subjected to thermal cycling.

It is recommended that the work described in this section be continued to determine the mechanism and energetics of the nucleation process. This will yield data on the thickness of different materials below which it should not be possible to prepare a continuous insulating layer, and the dependence of this minimum thickness on the nature of the underlying metal surface.

2.5.3 Insulating Films

2.5.3.1 Objectives

Film-type cryotron devices require short-free insulating films over the ground plane, and between control and gate elements,

as well as where leads cross. In order to obtain optimum performance for the complete cryotron, it is desirable to be able to make dielectric thickness small compared with the penetration depth in the superconductors. It is the main aim of this project to investigate the characteristics of some insulating films in the thickness range of 100 to 1000 Å.

2.5.3.2 Status

Currently no completely satisfactory insulating material has been developed. In the last 18 months comparison has been made of the insulating properties of calcium fluoride, magnesium flouride, germanium, aluminum oxide and silicon monoxide. If sufficient care is taken to prepare a smooth surface on the underlying metal film, short-free insulating films of the order of 600 to 700 Å thick may be prepared with each of these materials. No one material was observed to be any better than the others. On repeated thermal cycling between room temperature and $-195^{\circ}C$, only the germanium and the aluminum oxide did not tend to deteriorate. Short-free germanium films are obtained only when the system pressure was less than 1×10^{-6} mm. The method of obtaining the evaporated aluminum oxide films was not considered to be compatible with the

techniques used to fabricate cryotrons and was not pursued.

It has previously been shown[1] that the dielectric constant and composition of the silicon monoxide evaporated films vary with evaporation rate and residual pressure in the system. A thermodynamic analysis, included as Appendix IV, shows that the composition of the film is determined primarily by the temperature of the molecular beam and the partial pressures of various oxidizing gases in the vacuum chamber.

To date the most promising methods of obtaining insulators appear to be by the method of surface photolysis previously described and a technique of preparing metal oxide films, developed elsewhere in IBM. Attempts are being made to evaluate both these techniques.

2.5.3.3 Recommendations for Further Investigation

Since other methods appear more promising, no further investigation of these materials is planned at this time.

[1] D. York, Electrochemical Society Meeting, Indiana, May 1961.

3. MACHINE ORGANIZATION

3.1 OBJECTIVES

The goal of this project is the development of improved organizational systems and techniques for designing effective high-performance machines made of cryogenic components. Improved types of machine organizations specially suited to the peculiar properties of cryotrons will be developed; designs for specific functional units will be invented, constructed and tested; and automated methods of system and circuit design will be studied.

3.2 ORGANIZATIONAL FEATURES OF SUPERCONDUCTOR SYSTEMS (W. C. CARTER)

3.2.1 Objectives

Because of the multiplicity of choices available to machine designers using cryotrons, new criteria must be developed to evaluate organizational features. To help determine these criteria, theoretical studies will be conducted of the effect of the size, structure, versatility, and interrelationship of a machine's storage,

arithmetic, and logical units on its capabilities. Where possible, mathematical models will be used to obtain quantitative results.

Some machine organizational features, such as ease of use and effectiveness, can at present be evaluated only by trial and error. The production and evaluation of specifications or preliminary logical designs of machines using cryotrons will provide such information.

3.2.2 Status

The studies of multiplexed equipment design using mathematical models are reported in Appendix XI, Volume II, "Guides for the Organization of Machines Using Multiplexed Equipment." The following conclusions are reached:

1. Matching the numbers and types of multiplexed processors to the expected probability of occurrence of instruction types will:

   a. give high peak efficiency if the match is right,

   b. result in rapidly decreasing average efficiency if the combination of multiplexed processors is unbalanced.

2. Using balanced combinations of numbers and types of multiplexed processors will give maximum average efficiency if many combinations of instruction steps with different probabilities of occurrence are to be used.

3. The addition of stores to permit some commands to be temporarily skipped if the processor is not ready to execute them will rapidly increase the peak efficiency of problem solving, especially for balanced combinations of processors.

4. The increase in efficiency due to stores is very sensitive to the relative cost of storage stations.

5. The bunching of types of instruction steps will decrease multiplexing efficiency. The use of stores to permit commands to be processed out of order decreases this effect.

3.2.3 Recommendations for Further Work

The mathematical techniques already developed can be extended to cover classes of more complicated models.

3.3 CRYOTRON HIGH-SPEED MEMORY SYSTEMS (A. L. LEINER)

3.3.1 Objectives

The long-range objective of this project includes the design of a high-speed addressable cryotron memory. Capacities of about 2048 words of 48 bits are being aimed at, but exact specifications will not be determined until some of the work now underway has been concluded. The program is being undertaken in several stages, the first of which was the design of a 16-word addressable storage unit using the fastest in-line cryotrons now available. This was followed by the design of automatic checking and control circuitry using the same components. These are designed to permit sustained operation and testing of the memory over as wide a range of conditions as possible, including attachment to external room-temperature hardware. It is expected that the experience gained in observing the small-scale systems in operation, together with anticipated increases in the basic cryotron switching speeds, will provide a firm basis for extension of the designs to much larger and faster memory systems.

3.3.2 Status

The detailed system plans for the checking and control portions of the 16-bit experimental memory have been completed.[1] Logic and circuit layouts for these final sections of the over-all system are contained in Appendix IX, Volume II, "A Control System for Testing an Experimental 16-Bit Memory Using In-Line Cryotrons."

The checking and control units contain 440 in-line cryotrons. These are used for generating numerical data, address numbers, and control signals for the storage units. Stored numerical data written into the memory during a <u>write-cycle</u> can be read out during subsequent <u>read-cycles</u> and automatically compared with the output of the originating data generator. The system is designed so that its various subunits can be systematically tested independently of one another. For example, external controls permit a human operator to intervene in the program of operations in various ways, such as: starting or stopping different parts of the system, reloading storage cells, and varying the reading and writing rates. Sensing controls are provided to aid in observing

---

1 Project Lightning, Eighth Quarterly Progress Report, p. 71. Project Lightning, Ninth Quarterly Progress Report, p. 39.

the detailed performance of the system and in analyzing and correcting malfunctions.

Appendix IX contains an analysis of operating rates for each part of the system, assuming various feasible values for gate dimensions and resistivity. Since the speeds of cryotron systems depend critically upon circuit fan-outs, a general analysis of the effect of fan-out on system speed and component count is also included.

The layout plans for the 16-bit memory system, described in Appendix IV of the ninth quarterly Lightning report, were transmitted to the cryogenics development group at the Kingston Laboratory for detailed analysis of the substrate fabrication requirements.

Work continued on the design of high-speed hazard-free cryotron circuitry. Our objective is to design circuits which can operate reliably under conditons of wide variation in signal levels and pulse timing. This factor is of prime importance because of the loose tolerances presently associated with cryotron fabrication and the difficulty of inspecting and adjusting hardware located in the cryostat. A series of hazard-free asynchronous circuit types were designed and are being studied for possible use as clocking control stages.

Timing studies of this type can be greatly expedited through use of an analog computer coupled with a digital facility for handling the nonlinear component characteristics. A trial setup of a typical circuit simulation problem was made on an analog computer. Preliminary results indicate that useful solutions for small-scale circuits and systems can probably be attained much faster by using analog simulation instead of the previously used fully digital methods.

Work continued on the study of large-scale high-speed memory systems of the type reported on previously.* Revisions in the organization of the 2048-word selector switch have resulted in greatly reduced dissipation requirements and a considerably reduced component count. In collaboration with other circuit groups, work continued on the design of room temperature input-output driver circuitry suitable for high data-rate communication with the hardware located in the cryostat. Preliminary results confirm the validity of the data-rate estimates previously reported.*

---

* Proposal for Phase IV of Lightning, "Feasibility Study for a High-Speed Memory," IBM Research Center, February 1961.

3.3.3 Recommendations for Further Work

Further work is needed on designing and testing high-speed cryotron circuits that are able to operate reliably within the tolerance limitations of the current fabrication art. These circuits should ultimately operate with delays of about 1 nanosecond per stage, including interconnections. They must, moreover, operate with hazard-free timing at high data-rates, and should have low dissipation and low noise sensitivity.

Functional units embodying such improved circuits should be built and tested. These should be designed so as to derive as much meaningful information as possible from observation of their system behavior. This problem is greatly aggravated by the inherent inaccessibility of the hardware in the cryostat and the difficulty of making adjustments and modifications on the cryotron substrate. Appropriate emphasis should continue to be placed, therefore, on designing adequate input and output facilities for these test systems.

Efforts ought to be continued on the problem of devising system design techniques suitable for dealing with other major aspects of cryotron machine organization. The most urgent needs

here are for (1) adequate practical means for simulating circuit and system behavior, and (2) automated design aids for cryotron substrate layout and mask design.

A longer range objective should be the realization of large-scale cryogenic machine systems, such as the high-speed memory studied earlier this year. Further refinements and extensions of these designs should be planned.

3.4 FUNCTIONAL UNIT ANALYSIS (J. L. SANBORN)

3.4.1 Objective

The objective of this project is to help discover and solve various problems in the design and construction of cryotronic computers. Designs to meet the specifications proposed as part of the organizational features study will be provided by inventing functional units for such machines. Studies will be made of the characteristics and possible application of distinct types of cryotrons in these designs. Circuits necessary for these designs will be determined and assistance given in devising tests to determine the feasibility of constructing and using such circuits.

3.4.2 Status

Work on an asynchronous data-timed system was begun by E. D. Conroy. This system may require about 50 percent more components than a corresponding synchronous system, a small increase considering the numerous advantages of asynchronism. The system is divided into sections of logic with interlocks between sections that guarantee the presence of new data in one section and the ability of the next section to receive that data before advancing. Similar systems often allow data to appear only in every other section. This system is designed so that every section may contain data. Thus, if the final logical section is blocked, while waiting for an input-output unit, for example, the previous sections will continue processing until all sections contain new valid data at their outputs. Parts of this system are described in Disclosures 101,195, Asynchronous Cryogenic Logic Block, and 101,277, Control System for Asynchronous, Data-Timed Cryogenic Logic.

During the development of the asynchronous system a three-branch circuit was proposed for use as a general logic block. In order to determine the effect of the third branch upon circuit operation, a detailed analysis of three-branch circuits was performed.

This analysis appears as Appendix VIII, Volume II, "General Lumped-Constant Analysis of Three-Branch Cryogenic Loops."

The investigation of methods for the synthesis of Boolean functions with multiple-control cryotrons previously described* has been completed. The results of this investigation are given in Appendix X, Volume II, "The Implementation of Logic with Multiple-Control Cryotrons."

3.4.3 Recommendations for Further Investigation

1. Studies of methods of cryotronic asynchronous design.

2. Further study of the proposed synthesis method for purposes of evaluation and further refinement.

---

* Project Lightning, Ninth Quarterly Progress Report, March 31, 1961, pp. 45-47.

3.5 MECHANIZATION OF DESIGN AND ANALYSIS (W. C. CARTER)

3.5.1 Objectives

The first objective is to aid in the detailed design and testing of cryotron circuits. Programs which can simulate circuit action aid design and testing by providing knowledge of expected responses. In some cases, simulation may replace construction.

The second objective is to make possible the design of large cryotron computers by providing computer programs to work out design details and their conversion to evaporation-mask layouts. To do this, new methods of logical design must be devised, and programs for generating circuit layouts must be written.

3.5.2 Status

A study has been made of methods of designing sequential circuits using cryotrons and is included as Appendix VII, Volume II, "Sequential Cryotron Switching Circuits," by J. L. Rosenfeld. Because of the combination of storage and logic available in

cryogenic circuits, efficient sequential circuits can be designed using cryotrons.

Studies were begun of circuit layout by machine and the design of asynchronous circuits. The relevant work was collected from the published literature and from other departments at IBM.

3.5.3 Recommendations for Further Work

A need exists for more effective methods of simulating circuit and system performance. In order to accelerate the design of practical circuits, timing tolerance and noise analyses are required. These can be carried out efficiently by using analog-digital computer equipment.

Long-range requirements include the development of data-processing techniques for speeding up the extensive and time-consuming tasks of cryotron substrate layout (with minimized loop lengths, etc.) and mask design artwork.

4. SUMMARY AND CONCLUSIONS

4.1 DEVICE AND CIRCUIT STUDIES

A comparison of tin and indium cryotrons has shown that indium gates made in conventional evaporators have characteristics which are more reproducible than tin. In spite of this improvement, additional control of evaporation conditions must be achieved to obtain the maximum operating speed capabilities of in-line cryotrons.

A detailed analysis of the thermal problem using values of the coefficient of heat transfer to the bath determined by experiment has been made. The analysis has been extrapolated to a system of continuously operated, thermally coupled cryotrons. The results indicate that cryotron densities of several thousand per square inch can be operated at a kilomegacycle rate.

Experiments have shown that a field-free region should be provided to prevent the ground plane from trapping flux as a sample is immersed in liquid helium. The amount of flux which can be trapped by the earth's field is sufficient to reduce the critical current of a film by a factor of two.

4.2 MACHINE ORGANIZATION

Studies of multiplexed equipment design were continued, including some numerical analyses. The results confirm the earlier main conclusions that the numbers and types of processors should be matched to the instruction types and that there should be a store in which to form queues of instructions temporarily skipped.

The detailed system plans for the control and checking portions of the 16-bit experimental in-line cryotron memory were completed. Expected operating rates were calculated for various circuit parameters. Criteria were developed for determining the optimum fan-out for circuits.

Revisions were made in the organization of the 2048-word selector switch, resulting in reduced numbers of components and reduced power dissipation.

Work on asynchronous hazard-free circuits was continued, including analog simulation, in an effort to develop circuits that operate reliably over wide ranges of signal levels, pulse shape, and pulse timing. Such circuits involve, in part, three-branch cryotron loops, two for binary information and one for the null condition.

Studies have been started on automatic sequential circuit layout by machines.

Summary of Progress in Cryotronic Technology and Devices

R. B. DeLano, Jr.

ABSTRACT

This paper summarizes the status and discusses the important advances in the design and fabrication of devices which were made while the IBM low-temperature effort received support under Phase III of Project Lightning. Mention is also made of some of the pertinent work supported by IBM and of that supported under the earlier phases of the Lightning program. The major advances have been in the areas of basic material properties, determination of the factors affecting device reproducibility, circuit switching speed, and the limitation power dissipation imposes on the speed of a cryotronic computer. The most important problem to be solved is that of obtaining reliable insulating films. Recommendations are given for further work in solving this problem and in reducing other limitations.

INTRODUCTION

During the last 12 months that the IBM low-temperature effort has received Lightning support, work has continued in the direction of developing the technology and circuits for a kilomegacycle computer using the evaporated thin-film cryotron as a basic component. This paper discusses the progress, status, and recommendations for further work in the areas of technology, devices, and circuits.

The important characteristics of the gate film are discussed first. These include the edge effect, reproducibility, and the gains to be expected by using indium-alloy films.

Insulating films are discussed in the next section. The development of an insulating film which will be short-free is the major problem hindering the practical application of cryotronic circuits. Shorts occurring during device fabrication have been reduced by source designs which minimize spitting, and several new techniques are suggested which may yield more rugged insulating films.

The residual gases which are present in the conventional vacuum system and their effect on the characteristics of the gate film have been determined for both indium and tin films. This work, together with a discussion of masks, substrates, ground plane, and methods of coupling from one substrate to another, will be found in the section on fabrication techniques.

The paper concludes with discussions of cryotron gain, time constant, power dissipation, and the limitations which power dissipation imposes on circuit speed.

GATE FILM

The principal requirement of a cryotron gate film is that it have a sharp transition between superconducting and normal state under the influence of a specified current in the control. This requirement also implies reproducibility and freedom from hysteresis. In addition, a large resistance is desired when the gate is driven normal. The current-carrying capacity of the superconducting gate must be larger than the critical control current when the gate must carry the control current of another cryotron. Moreover, a large ratio of critical gate to critical control current reduces the reproducibility problem.

In terms of more fundamental parameters, the resistivity should be as high as is consistent with a small penetration depth, and homogeneity of composition and structure. The grain size should be small and the critical field uniform from one sample to another.

Discovery of the edge effect[1, 2] was a major breakthrough which made it possible to develop practical methods of securing sharp transitions and films which had reproducible critical fields. Since the critical field of a film increases as the film becomes thinner, driving the gate film normal by an external field causes the current to concentrate in the thin edges. Therefore, the critical field is determined by irregularities in the geometry of the edges, and imperfections which tend to concentrate there. The edge effect can be eliminated by several practical methods, which will be discussed later. Each of these relies on causing the thin portion of the film edges to break up into isolated islands which cannot conduct current.

It is obvious that homogeneity of composition can affect the transition width. Dilute alloys, however, can be made sufficiently homogeneous to have very sharp transitions.[4] This is particularly true of indium alloys where rapid diffusion can take place to provide homogeneity and when the amount of the minor constituent is close to the value which gives a minimum in the critical temperature as a function of composition. The practical minimum transition width which has been obtained to date is 1 to 3 percent of the applied critical field.

Magnetic hysteresis is undesirable in that the bias must be reduced and additional driving field supplied to prevent latch-up. In the films which have been made in our production evaporators the magnetic hysteresis has been about 10 percent of the critical field. However, hysteresis can be reduced by controlling the grain size and film thickness and is not considered a serious problem.

The ratio of the critical field of a film which is free of the edge effect to the critical field of bulk material can be obtained from the London theory[1] which leads to the formula:

$$\frac{H_c^f}{H_c^b} = \frac{1}{\sqrt{1 - \frac{2\lambda_\epsilon}{t} \tanh \frac{t}{2\lambda_\epsilon}}}, \qquad (1)$$

where t is the film thickness and λ_ϵ is an effective penetration depth at the operating temperature which is a function of film thickness and resistivity.[3] The agreement between this formula and experimental values is good once the proper value of λ_ϵ is chosen.

The reproducibility of critical field for biased operation with in-line cryotrons must be very good if maximum operating speed is to be obtained. Although the exact value is not known, preliminary experiments indicate that the critical field should not vary by more

than ± 2 percent, assuming practical transition widths, a reasonable amount of overdrive, and a small substrate temperature rise. Crossed-film cryotrons do not have as severe requirements on the critical field, since a large incremental amplification can be obtained over a substantial portion of the characteristic by using a large gate to control film width ratio. The time constant is increased, however, when this is done.

The critical current of a film is not nearly as well understood as the critical field or transition width. The unknowns are basic, and are concerned with determining the critical current density and relating it to the critical current of a film. The following relationship is mainly empirical and agrees only qualitatively with experiment:[5]

$$I_{gc} = W_g \, H_c^b \, \tanh \, t/\lambda_\epsilon . \qquad (2)$$

Fortunately, the mode of operating cryotrons is such that relatively large variations in critical control current can be tolerated. Thus critical current is not a real device problem, although there is no doubt that an increased reproducibility in critical current would lead to higher gains at higher speeds.

Indium films are substantially better than tin with respect to reproducibility. The variation in critical temperatures of a group

of indium films evaporated at different times was only one-sixth that obtained for tin. This probably is the result of the higher purity of the indium films and the fact that strains in indium are relieved more readily.

Recent tests[5] of in-line indium gate cryotrons indicate that our present fabrication techniques are inadequate to produce the cryotrons needed in high-speed circuits. Edge breakaway, increased control of thickness and purity, and increased control of shadowing in control edges are required to produce cryotrons which can be interconnected in high-speed circuits. The techniques needed to achieve these goals are known but have not yet been adequately developed in our production system. Work to this end is in progress.

Indium alloys offer the possibility of increasing the resistivity to a higher value than that of tin without an appreciable increase in penetration depth, decrease in transition sharpness, or variation of critical field.[6] Homogeneity rather than increase in penetration depth determines the maximum usable resistivity ($\sim$1.5 micro ohm centimeters) which can be obtained.

The diffusion of lead into tin gates is a difficulty which must be overcome, and attempts are being made to develop diffusion barriers

of a refractory metal such as vanadium. The high diffusion coefficient for indium is an advantage, of course, in achieving a homogeneous alloy.

INSULATING FILMS

Thin-film cryotronic devices require insulating films which should ideally be about 1000 Å thick. A similar or thicker film is also needed to cover all of the films for protection. The occurrence of shorts - either as a result of imperfectly evaporated layers during fabrication, or of subsequent deterioration of the insulation - has been the major stumbling block in the development of the cryotronic technology.

A great deal of effort has gone into attempting to define the insulation problem, and some of the most pertinent features are discussed here.

The shorts which occur during fabrication appear to be caused primarily by unwanted contamination or spitting from the metal and insulating material sources in the evaporator. Spitting from the metal sources produces rough surfaces which are difficult to cover. Refractory metals (such as molybdenum and tantalum) when placed in contact with the melt will remove the scum of metal oxide, which is

one cause of spitting.[1] The indirectly heated source[7] has been modified to provide for thermal contact between the heater and the melt container to prevent the occurrence of hot spots in the melt which would cause spitting.

Spitting from the silicon monoxide source has been reduced by using the outgassed pellets which are now available. These are used in an indirectly heated source and are kept from touching the sides of the source by a wire which passes through the center of the pellet.

Some of the shorts which occur after fabrication may also be caused by incomplete coverage of the metal layer. There is a strong possibility, however, that stresses produced by the evaporation conditions[8] and differences in the thermal expansion coefficient of the insulation film and the rest of the structure may be causing these shorts. This belief is substantiated by the buckling and peeling of the insulating films which have been observed. Recent work not supported by this program has shown that stress in evaporated SiO films can be controlled and can be made positive, zero, or negative. The effect of controlled stress on the shorting problem in devices is being determined.

A number of other insulating materials have been tried, with varying degrees of success. These include calcium fluoride, magnesium fluoride, aluminum oxide, and germanium. No material gave a substantial improvement over silicon monoxide. A new technique for preparing metal oxides is now being tried. Metal oxides whose vapor pressure is higher than that of the metal itself can be sublimed from a heated tube through which oxygen is passed without causing a large increase in the pressure of oxygen in the system. Such a source should be free from spitting. Molybdenum oxide films made in this manner are amorphous and do not fracture in the violent manner of silicon monoxide when scratched. No cryotrons have been made yet using this material, but the results are sufficiently promising that a suitable source is being installed in one of the device evaporators.

A distinctly new technique is also being evaluated. Butadiene ($H_2C = CH - CH = CH_2$) and some other hydrocarbons can be polymerized by ultraviolet light after they have been adsorbed on a surface. Since this process involves adsorption, the sticking coefficient should be high before the first monolayer is formed and the insulating film should be free of pinholes. Evaporated metal film capacitors with an insulating film of only 50-100 Å have been made and found to withstand temperature cycling. The next step will be to make and test devices made with this technique.

At present the yield of short-free devices from the evaporator fluctuates wildly, but is much better than before the importance of minimizing spitting was recognized. During some periods 90 percent of the devices are short-free, followed by periods of much lower yield. The improvement in the yield of short-free devices has focused attention on the number of shorts that occur during testing. Nearly every one of the subtractor circuits developed shorts during the testing operation, usually immediately after immersion in liquid helium. While these could be cleared so that testing could proceed, the problem is serious with complex circuits and certainly must be solved before a serious development effort is undertaken. On the other hand, a number of simple circuits have withstood repeated immersions over a period of several months without developing shorts, which indicates that the problem should be solvable.

While the work appears promising, there is no assurance that a solution will be found to this complex problem during the next few months.

FABRICATION TECHNIQUES

A large effort has been expended over the last three years to determine what type of vacuum system should be used in making cryotrons. The principal consideration has been to eliminate the edge effect by allowing the sloping portions of the edges to break up into discontinuous islands. The critical parameters are the residual gases, the substrate temperature, and cleanliness. The residual gases which are important and the maximum amount which can be tolerated when tin is being evaporated at a rate of 100 Å per second are as follows:[9]

Gas	P_{max} (mm Hg)
O_2	5.10^{-8}
H_2O	4.10^{-7}
CO_2	8.10^{-7}

The amount of gas which can be tolerated while indium films are being evaporated has also been determined.[10] Indium films are not as critical with respect to residual gas.

A special ultra-high vacuum system was developed so that the sensitivity with respect to various residual gases could be determined.[11] This system did not use oil pumps because oil is difficult

to trap completely and the sensitivity of the films to oil vapors was to be determined. This work led to showing the practical usefulness of a liquid helium finger pump in a dynamic system.[12]

An analysis was made of the residual gases in a well designed and trapped system.[13] The amount of oil vapor was not a problem but oxygen, water vapor, and carbon dioxide were. Selective pumping means were designed for the critical gases. Coils containing liquid nitrogen were found to be effective in pumping water vapor and carbon dioxide. A titanium getter can be used for oxygen although usually the evaporation of silicon monoxide just before the shutter is opened to deposit the gate is sufficient. The device systems were modified so that the critical gases in the system were kept below the limits specified above for tin although there was some question as to the residual gas level between the mask and substrate.

Controlled substrate heating was achieved by clamping an aluminum block containing a thermocouple to the substrate. The block was then heated by radiation. The principal problem with this method was the long wait required before the substrate returned to room temperature. Tin films made in the device systems with a substrate temperature of 62°C have transitions that are as sharp as those obtained when the edges of the film are removed mechanically.

Sufficient knowledge has been obtained to provide a good understanding of the vacuum system required to obtain films having sharp transitions. Moreover, the vacuum has been found adequate to insure that connections made between successive layers of evaporated films will be superconducting. Consequently, cross-latching, which has been shown to slow down the speed of a flip flop,[14] is not required.

Source design has been discussed under insulating films. One point which was not mentioned is that the heat radiated to the substrate and mask should be minimized to prevent shadowing around the control and interconnecting films. Rate monitors are necessary to obtain adequate control of film thickness.[15] Indium alloy films can be made by evaporating a charge of the desired composition to completion relying on diffusion in the film to eliminate the inhomogeneity caused by the difference in vapor pressure of the two constituents.

During the course of the work the mask and substrate heating mechanism were improved to provide registration between successive layers of better than 0.0005 inch. Registration between the control and gate of an in-line cryotron must be extremely accurate. The misregistration caused by inaccuracies of the mask punch can be eliminated by using the same mask for both the control and the gate and using other masks to make the connections.

Most of the cryotrons and circuits have been made by using punched metal masks. A special pantograph was used to provide a registration of ± 0.001 inch. The main advantages of this method are the rapidity with which a mask can be made and the good edge definition. Masks engraved from heavy copper have been used for devices which require rounded corners. Photoform glass and etched metal masks have also been used.

When punching complicated masks the detection of simple errors becomes a problem. Errors which would cause shorts can be found by making opaque negatives of the insulating layer masks and registering these masks with the masks used to make the associated metal films which are to be insulated. The masks should be registered using the same index points as are used in the substrate handler. By attempting to shine light through the array, errors can be detected. Each of the masks should be moved a small amount to account for misregistration, variation in source position, etc.

The method of making insulation films by surface photolysis discussed previously, has been extended to the etching of tin and lead films. The gas used in this case was methyl iodide, which formed a volatile compound with the metal where it was exposed to ultraviolet light. This method can probably be combined with the

formation of insulating films to yield a technique of producing circuits in which the masks are solid, thick pieces of glass, with which finer resolution can be obtained.

Glass and single-crystal sapphire are the only substrate materials which have been used for circuit fabrication. The number of high-speed cryotron circuits which can be operated on a substrate is limited by the heat transfer between the substrate and the bath. This transfer can be increased by using a substrate having high thermal conductivity[16] since only a fraction of the total number of computer circuits will be in operation at any one time. Sapphire is considered too expensive for practical application and metal substrates are under investigation.

The ground plane serves to confine the magnetic fields and reduce the stored energy and thereby increase the operating speed and reduce cross coupling. All the cryotrons and circuits which have been made have used evaporated lead ground planes. Flux trapped in the lead has been a recurrent problem, particularly when determining device characteristics which are outside the normal operating range. There are several possible solutions. One which is being investigated is to use a hard superconductor as a substrate, such as niobium, with an additional film of a high critical temperature material. Films of

niobium nitride having a critical temperature of 14°K have been made, and work is planned to test their suitability for ground planes and other uses.

Several methods of intersubstrate coupling have been given preliminary evaluations and appear attractive. Tests on a superconducting transformer have shown that a coupling coefficient of 0.95 can be obtained. Low-impedance transmission lines made of lead foils with thin mylar tape insulation can also be used. Such a line was used to couple the two halves of a flip-flop which were on different substrates, and the time constant for current transfer was found to be 5 nanoseconds. The inductance of the connections was estimated to be five times that of the line. This inductance is large because of the difficulty of continuing the ground plane underneath the point at which the connection is made between the circuit and the transmission line without causing a short. A superconducting lead paint has been developed recently which will make this connection. The paint consists of lead powder, acetic acid, and vynyl butryal resin with alcohol as a solvent. The acid cleans the lead particles so that they will make superconductive contact and will also clean the film and foil.

Lines similar to the one used for intersubstrate connections should be satisfactory for drive and output. Measurements on this type of line indicate that it is capable of transmitting a pulse having a rise time less than one nanosecond. There is some question, however, whether this type of line can be produced with sufficiently uniform characteristics to avoid reflections.

In conclusion, the previous discussion has indicated a number of items which are not considered serious because the direction to take is fairly clear. However, much remains to be done to incorporate all these changes into a practical device technology. Many of these will require modifications to the fabrication units and improved control over such parameters as evaporation rates, substrate and mask temperatures, and grain size of films.

CRYOTRON CHARACTERISTICS

The cryotron is the basic device used in all circuits. The important parameters of interest other than those mentioned before are the gain, both over-all and incremental, and the L/R time constant. The switching speed of the cryotron itself is sufficiently faster than its speed in typical circuits as to warrant only minor attention.

Two types of cryotrons with which this project has been concerned are the crossed-film and the in-line. The crossed-film cryotron is useful where high packing density is desirable and in lower-speed circuits. The in-line cryotron has been developed recently. Its main advantage is to obtain high speed in circuits having a long loop.

The amplification factor is the ratio of the critical gate current to the critical control current. These characteristics have been discussed in the section on gate film characteristics. For the crossed-film cryotron the amplification factor is also proportional to the width ratio of the gate and control films. Consequently the amplification factor becomes:

$$G = \frac{W_g}{W_c} \tanh t/\lambda_\epsilon \sqrt{1 - \frac{2\lambda_\epsilon}{t} \tanh \frac{t}{2\lambda_\epsilon}} \qquad (3)$$

The experimental results agree qualitatively with this formula. The width ratio is chosen to be greater than one so that one cryotron can drive another, and because experiments have shown that cryotrons having a width ratio of one have small incremental gain. Increasing the amplification by increasing the width ratio will either increase the control inductance or decrease the gate resistance, making the time constant longer. The ratio of film thickness to effective

penetration depth at the operating temperature is chosen to give a gain near the width ratio; too small a value would require an excessive width ratio, and too large a value would also increase the time constant by reducing the resistivity. As mentioned previously, the gate resistivity can be increased by alloying, to be the maximum value which will give sharp transitions. The circuit time constant is then determined by loop geometry.

The operation of the in-line cryotron is made possible by the unsymmetrical field which exists above and below a film carrying current over a ground plane. The field above the conductor is essentially zero, and that between the film and the plane is proportional to the control current and the width of the film. A current flowing in a superimposed control in opposite direction produces a field which opposes that produced by the gate current. The current-carrying capacity of the gate increases with the control current until the control field above the gate equals the critical value, whereupon the gate current capacity drops sharply to zero.

The gate and control widths of the in-line cryotron are usually made the same. If the control is narrower than the gate, the incremental gain becomes zero for small values of gate current. A wide control film tends to reduce the over-all gain.

While the above discussion is based on the critical field concept, using the critical current hypothesis gives formulas for computing the amplification characteristic which are closer to the experimental curves.[17] These formulas show that while the amplification factor can never exceed one, large values of incremental gain can be obtained.

Experimental results have shown that the incremental gain is constant for gate current values up to 0.7 of the critical gate current. The variation of the maximum incremental gain as a function of the ratio of film thickness to penetration depth has been determined experimentally for tin and indium.[18] Incremental gains as large as ten have been observed; consequently, operating gain greater than one can be obtained easily with bias. A second control superimposed on the first can be used to provide the bias or as a second control for coincident current selection. The second control has been shown to produce essentially the same amplification characteristic as the first. Bias also has the advantage of reducing the amount of control current required to produce resistance in the gate and therefore the amount of power dissipated.

The time constant of the cryotron itself is independent of the length, but that of the loop containing the cryotron will be

decreased as the ratio of cryotron length to loop length is increased. For this reason the in-line cryotron is especially useful for driving large inductance loops such as those used for memory selection, input-output, and coupling between substrates. One of the disadvantages is the closer tolerances required of the gate film characteristics, which have been discussed earlier. The increase in speed is obtained only at the expense of additional power dissipated, as will be discussed in the next section.

SPEED AND POWER LIMITATIONS

The speed and power of a cryotron are related as they are for most components. The speed is proportional to the loop L/R time constant[19] as long as the resistance of the cryotron does not approach the characteristic impedance of the line forming the loop. The L/R time constant of the circuit does not change as both circuit dimensions are scaled linearly. An approximate analysis of the switching time of coupled circuits has been made recently[20] which takes into account the change of inductance produced when the gate changes state. Calculations give a

stage delay between 0.5 and 1.5 the L/R time constant, which is 3.4 nanoseconds for a typical practical loop. The speed of the cryotron itself is not the significant factor in determining circuit speed.

The inductance can be calculated approximately by using the "flux per unit current" concept, but a more accurate formulation requires that the energy of the superconducting electrons be taken into account.[21] The difference between the two values increases as the insulation becomes thinner, but is less than 10 percent for the 5000 Å thick films being used at present.

The resistance should be computed by using the normal resistivity which corresponds to the film thickness and evaporation conditions being used. Typical values of the surface resistivity in ohms per square are $0.59 \cdot 10^{-2}$ for lead and $0.16 \cdot 10^{-2}$ for indium when the film thickness is 5000 Å.[22]

Time constants as short as 10 nanoseconds have been measured for a flip-flop using crossed-film cryotrons and driven by a pulse having a short rise time. A similar circuit using in-line cryotrons was found to have a time constant less than 3 nanoseconds. The critical test will be to measure the delay per stage of two coupled flip-flops made using the high quality techniques discussed previously.

The power dissipated in a flip-flop each time a current, I, is switched from one side to the other is proportional to I^2R_g where R_g is the normal gate resistance. For an in-line cryotron the formulas are:

$$H_c = \frac{0.4\pi I}{W}, \quad \text{and}$$

$$R_g = \frac{\rho_s \ell_g}{W},$$

where H_c = control field

ρ_s = normal surface resistivity of gate material

ℓ_g = gate length.

Hence the power dissipated is:

$$P = \frac{I^2R}{4} = 0.16\, H^2 \rho_s\, W\, \ell_g. \tag{4}$$

The magnetic field, H_c, is fixed by the overdrive necessary to obtain high speed and tolerances. The surface resistivity is determined by speed and transition width, as discussed previously. The length of the gate is determined by the speed and loop geometry. The only variable left is the line width. Also note that all the factors should be made large to obtain maximum speed, except the line width, and the time constant is independent of line width. The minimum practical line width is determined by mask construction and registration with the substrate.

The limitation on power dissipation is determined by the change in critical field, ΔH, caused by the temperature rise, ΔT,

$$\Delta T = \frac{P}{K} \alpha \Delta H,$$

where K is the thermal conductance from the gate to the bath. Consequently, the fractional change in critical field becomes:

$$\frac{\Delta H}{H} \alpha \frac{H \rho_s A'}{K},$$

where A' is an equivalent gate area which is larger than the actual gate area by a factor which depends on the thermal conductivity of the substrate.[16] Because of the random nature in which most computer circuits function, the maximum change in critical field should be combined with the other tolerances affecting gate film reproducibility. Obviously, the thermal conductance to the bath must be maximized and it may be possible to increase this conductance by a large amount. Since it is primarily determined by the heat transfer across the solid-liquid interface, the internal thermal conductivity of the substrate should also be large.

Calculations have been made of the maximum density of in-line cryotrons operating at a kilomegacycle rate on a substrate having high thermal conductivity. The results are given in Appendix II of this report. They show that while power dissipated does limit

the cryotron density when operating at high duty factor, actually densities of a few thousand cryotrons per square inch are possible on substrates having high thermal conductivity.[23] The duty cycle given in this appendix is the duty cycle of one gate; consequently, a duty cycle of 0.5 corresponds to resistance in one side or the other of the loop at all times and represents the maximum speed at which the flip-flop can operate. The figures in the first column of Table I are very conservative since the change in critical field is only 6 percent of the driving field. The values in the last column represent a good estimate of what can be expected in practice.

If the loops in the circuits operating at high duty factor can be made sufficiently short to obtain adequate speed with crossed-film cryotrons, the reduced tolerance problem with this type of cryotron would allow a larger temperature rise and increased packing density. There is also an excellent possibility that the thermal conductance to the bath can be increased for metal substrates, and this question is being studied.

CONCLUSIONS

At the present, insulation is the biggest difficulty in achieving practical hardware with circuits employing cryotrons. Insulating films are much better than they were a year ago and several new ideas are promising, but the greatest emphasis should be in this area.

The other material problems are under control in that the basic factors are known and the direction of future progress is identified. The details which need to be worked on mostly pertain to improved methods and controls in fabrication.

During the last year, cryotron switching speed has been investigated both theoretically and experimentally. The results of the analysis have been combined with an investigation of heat dissipation. Circuit operation in the nanosecond region seems possible, but experimental verification cannot be made until device fabrication is improved.

A number of miscellaneous items including intersubstrate coupling and input-output lines have been reviewed and preliminary experiments performed which indicate that the problems here are of an engineering nature and can be solved.

REFERENCES

1. G. J. Kahan, R. B. DeLano, Jr., A. E. Brennemann, R. T. C. Tsui, "Superconducting Tin Films of Low Residual Resistivity," IBM Journal, Vol. 4, pp. 173-183 (1960).

2. R. B. DeLano, Jr., "Edge Effects in Superconducting Films," Solid-State Electronics, Vol. 1, pp. 381-387 (1960).

3. W. B. Ittner, III, "The Critical Fields of Thin Superconducting Films," Project Lightning, Fifth Quarterly Progress Report, pp. 89-111.

4. W. B. Ittner, III, "Physical Characteristics of Cryogenic Components," Project Lightning, Second Quarterly Progress Report, p. 74.

5. A. E. Brennemann, "A Memorandum on Results of Tin and Indium Cryotrons," Project Lightning, Tenth Quarterly Progress Report, Vol. II, pp. 1-21.

6. A. M. Toxen, "Characteristics of Bulk and Thin-Film Superconducting Alloys," Solid-State Electronics, Vol. 1, pp. 363-367 (1960).

7. E. M. DaSilva, "Evaporation Source with Controlled Characteristics," Rev. Sci. Instr., Vol. 31, p. 959 (1960).

8. J. Priest, H. L. Caswell, "Residual Stress in Silicon Monoxide Films," to be presented at American Vacuum Society Symposium, October 1961.

9. H. L. Caswell, "Effect of Residual Gases on Superconducting Characteristics of Tin Films," J. Appl. Phys., Vol. 32, pp. 105-114 (1961).

10. H. L. Caswell, "Characteristics of Indium Films Deposited in the Presence of Various Residual Gases," submitted to J. Appl. Phys.

11. H. L. Caswell, "An Oil-Free Ultra-High Vacuum System for the Deposition of Thin Films," Vacuum Symposium Transactions, pp. 66-71 (1959).

12. H. L. Caswell, "A Liquid Helium Trap for High Pumping Speed at Low Pressures," Rev. Sci Instr., Vol. 30, p. 1054 (1959).

13. H. L. Caswell, "Analysis of the Residual Gases in Several Types of High-Vacuum Evaporators," IBM Journal, Vol. 4, pp. 130-142 (1960).

14. M. K. Haynes, "Transient Analysis of Cryotron Networks by Computer Simulation," Project Lightning, Sixth Quarterly Progress Report, Vol. II, pp. 47-84.

15. G. R. Giedd, M. H. Perkins, "Evaporation Rate Monitor," Rev. Sci. Instr., Vol. 31, pp. 773-775 (1960).

16. H. Sobol, "Time Average Thermal Properties of a Computer Utilizing Thin-Film Superconducting Elements," Project Lightning, Tenth Quarterly Progress Report, Vol. II, pp. 23-79.

17. Project Lightning, Seventh Quarterly Progress Report, p. 15.

18. A. E. Brennemann, "A Memorandum on the Gain Characteristics of Indium Cryotrons," Project Lightning, Ninth Quarterly Progress Report, pp. 89-116.

19. N. H. Meyers, "Electrical Switching-Speed Considerations in a Simple Thin-Film Superconducting Circuit," Project Lightning, Sixth Quarterly Progress Report, Vol. II, pp. 107-132.

20. W. B. Ittner, III, "Switching Speeds in Thin-Film Cryotronic Loops," Project Lightning, Ninth Quarterly Progress Report, pp. 61-116.

21. N. H. Meyers, "Inductance in Thin-Film Superconducting Structures," Project Lightning, Ninth Quarterly Progress Report, pp. 117-166.

22. Project Lightning, Ninth Quarterly Progress Report, p. 96.

23. Project Lightning, Tenth Quarterly Progress Report, Vol. II, p. 64.

Summary of Progress in Cryogenic Machine Organization

A. L. Leiner

ABSTRACT

Emphasis in cryogenic machine organization last year shifted from crossed-film cryotron circuits to high-speed circuits and functional units using in-line cryotrons. A series of high-speed logical building blocks was developed. Detailed circuitry layouts based on these were made for a 660-cryotron memory and memory-test system.

INTRODUCTION

The cryogenic machine organization effort last year concentrated on two main areas: (1) the design of high-speed in-line cryotron circuits, and (2) the design of high-speed prototype units utilizing these circuits. This concentration on high speed represented a shift in over-all program emphasis. The former goal of achieving fast computing by using very large numbers of crossed-film cryotrons, subsequently shown to be relatively slow, gave way to the concept of a much smaller system built of high-speed components.

It had long been recognized that cryogenic technology, through the use of batch fabrication techniques, offered tremendous future potential for building very large machines at very low cost per element. Following this approach, fast throughput would be got by combining wide concurrency of operation with massive replication of parts, the latter being made practicable by the very low unit costs. The inherent high-speed potentialities of cryotrons, on the other hand, did not become clear until more recently. The past year's work has shown that the basic processing speeds of simple cryotron circuits are about as fast as the highest speeds projected for any other known kinds of components. It also appears now that techniques suitable for fabricating low-speed circuits can, with relatively slight improvements, be made

capable of fabricating very high-speed circuits. High speed, in short, seems largely a matter of circuit design, logical design, and circuit layout technique, rather than fabrication technology.

HIGH-SPEED CIRCUITS

Six principal properties characterize the new high-speed circuits. These may be summarized briefly as follows:

1. In-line cryotrons are used in place of the previously used crossed-film cryotrons.

2. Two-level input logic is used.[1] This takes the form of two-input AND-gates and OR-gates with either positive or negative (dualized) polarity. All gates have the same basic structure; they differ only in the direction and magnitude of the input currents applied to them. This fan-in of two seems adequate for most applications, even though not optimum. The availability of three or more inputs would be more efficient logically, but structures of this complexity are more difficult to build, and tolerance problems would be worse.

3. Simple two-path loops are used throughout.[2] Net current flow in these loops is unidirectional. The possibility of unwanted back currents and sneak paths, which may affect more

elaborate circuit configurations,[3] is eliminated.

4. Moderate fan-outs are used, generally ranging from 4 to 8. The exact fan-out is usually not critical[4] and compares favorably with the drive capability of other components.

5. Short wiring lengths are used, a critically necessary condition for high speed. This requirement is by far the most important single factor affecting circuit speed. The operating time of a circuit loop is nearly proportional to the length of the wiring, expressed in units of one gate length. In order to achieve top speed, therefore, careful attention must be paid to positioning the components and routing the wiring in an optimum fashion.[5]

6. Self-resetting circuits have been used in the more recent designs.[6] In these circuits the output of each stage provides signals for both setting and resetting all of the loops that it drives. As soon as the proper combination of signals appears on the input "set" leads of a driven stage, the stage flips (becomes "set"), because the setting logic has introduced resistance into the unwanted current path. As soon as this combination disappears as a result of some of the driving stages changing state, the combination of signals activating the "reset" input logic appears, thereby introducing resistance into the current-carrying path.

Thus, current in the driven stage is forced back into its original path immediately, without need for a separate special resetting signal later on. Because of the additional fan-outs needed for the resetting signals, the time-constant for this type of circuit is slightly longer than it would be if resettings were triggered by separate reset-driving circuits. The elimination of special resetting circuits, however, results in a marked decrease in component count and dissipation, and, therefore, is believed to represent a net over-all gain in operating effectiveness.

HIGH-SPEED FUNCTIONAL UNITS

In an effort to realize high-speed units built of these circuits as soon as possible and to gain experience in optimized layout procedures, a series of small-scale functional units was designed. The largest of these contains 660 in-line cryotrons and can carry out some simple arithmetic, storage, and control processes typical of more ambitious systems. The system is designed so that it can be built and tested in sections. When operated as an integrated unit, it functions as a self-controlled 16-bit memory[7] and memory-test unit.[8] Provision is made for

extensive external intervention in the operation of the system, as needed. The input-output is designed so that malfunctions can be efficiently analyzed and useful information derived on the effects of externally controlled parameter variations on system performance. Through this approach to the problems of practical cryotron hardware construction, we expect to extend our efforts later on to the design and construction of much larger and faster cryotronic computing systems.[9]

REFERENCES

1. Project Lightning, Ninth Quarterly Progress Report, Appendix IV, p. 183.

2. Project Lightning, Ninth Quarterly Progress Report, Appendix IV, p. 187.

3. Project Lightning, Tenth Quarterly Progress Report, Appendix VI, pp. 147-152.

4. Project Lightning, Tenth Quarterly Progress Report, Appendix IX, p. 275.

5. Project Lightning, Ninth Quarterly Progress Report, Appendix IV, p. 217.

6. Project Lightning, Ninth Quarterly Progress Report, Appendix IV, p. 190.

7. Project Lightning, Ninth Quarterly Progress Report, Appendix IV, p. 175.

8. Project Lightning, Tenth Quarterly Progress Report, Appendix IX, p. 217.

9. Proposal for Phase IV of Lightning, "Feasibility Study for a High-Speed Memory," February 1961.